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Modeling Relevant to Safe Operations of U.S. Navy Vessels in Arctic Conditions

Physical Modeling of Ice Loads

Arnold J. Song, James H. Lever, and Sarah W. Bates

June 2016

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Cold Regions Research and Engineering Laboratory

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Abstract

The U.S. Navy may need to operate its existing surface ships in Arctic marginal ice zones with ice concentrations up to 40%. To achieve this goal, the Navy must determine safe operational speeds as a function of ice concentration, floe size, and ice strength for its vessels. However, existing ice-impact models and safe-speed guidance for ships have derived from physical modeling and full-scale experience with ice-capable hull forms that have shallow entry angles to promote flexural ice failure preferentially over crushing failure. These models and associated guidance are unlikely to provide accurate estimates of ice forces on the more vertical-sided hulls that are characteristic of U.S. Navy vessels.

To address the lack of datasets relevant to the ice impacts on U.S. Navy vessels or like hull forms, this report proposes a series of 1:5 scale tests of ice impacts with a simplified “indentor” to obtain the data needed to inform and validate numerical models of ice impacts with Navy ships. These large-scale tests will provide important benchmark data to support the development of numerical testbeds where ice-impact forces under various operational scenarios are estimated, thus providing effective safe-speed and design guidance for existing Navy ships in Arctic marginal ice zones.

Contents

Illustrations

Figures

Tables

Preface

This study was conducted for the Office of Naval Research under MIPR# N0001415MP00317, “Modeling Relevant to Safe Operations of U.S. Navy Vessels in Arctic Conditions.” The program manager was Dr. Paul Hess in Code 331, Structural Reliability and Seabasing Technologies.

The work was performed by Dr. Arnold J. Song (Terrestrial and Cryospheric Sciences Branch, J. D. Horne, Chief) and Dr. James H. Lever and Sarah W. Bates (Force Projection and Sustainment Branch, Dr. Sarah Kopczynski, Chief), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Loren Wehmeyer was Chief of the Research and Engineering Division of ERDC-CRREL; and Kevin Knuuti was the Technical Director. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

CHC	Canadian Hydraulics Center
CONOP	Concept of Operation
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
DEM	Discrete Element Method
DYPIC	Dynamic Positioning in Ice
EG/AD/S	Ethylene Glycol, Aliphatic Detergent, Sugar
ERDC	Engineer Research and Development Center
FG or FGX	Fine Grained
GE	Granular Ethanol
HSVA	Hamburg Ship Model Basin
IACS	International Association of Classification Societies
IMO	International Maritime Organization
IOT	Institute for Ocean Technology
IPCC	Intergovernmental Panel on Climate Change
KIOST	Korea Institute of Ocean Science and Technology
KORDI	Korea Ocean Research and Development Institute
NRC-C	National Research Council of Canada
POLARIS	Polar Operational Limit Assessment Risk Indexing System
Polar UR	Unified Requirements for Polar Ships
RCP	Representative Concentration Pathways
S&T	Science and Technology
SNAME	Society of Naval Architects and Marine Engineers
SSC	Ship Structure Committee
USCG	U.S. Coast Guard
WMO	World Metrological Organization

Executive Summary

The Arctic Ocean is likely to experience an increase in commercial shipping, resource exploration, tourism, and geopolitical activity as sea ice extent and thickness continue to decline. To safeguard U.S. interests, the U.S. Navy may be asked to operate in marginal Arctic ice conditions with up to 40% ice cover.

This raises an important question: At what speeds may existing Navy surface ships safely operate under various combinations of ice thickness, strength, and concentration?

To inform and validate the designs of ice-capable vessels, naval architects have traditionally used physical modeling to measure the vessels' resistance, propulsion, and maneuvering characteristics using a scaled down replica of a particular hull form. Data from full-scale trials are helpful for refining and validating physical and numerical modeling techniques but can be difficult and expensive to obtain. To date, numerical modeling has played a lesser role: semi-empirical theories have estimated ice–ship impact forces to establish the structural requirements that ships must satisfy to achieve the desired Polar Class designation.

Advances in numerical methods and computing power suggest that numerical modeling could play an important role in analyzing ship performance and safety in ice-covered waters, especially when determining ice-impact forces on hulls and appendages and assessing the effects of ship speed and maneuvering. Validated numerical models can be run in a Monte-Carlo fashion to determine load-return periods. Such simulations will aid in ship design and can be used in real-time simulators for training and to seek best-practice operational guidelines for traveling in ice-covered waters.

The key to developing numerical models is to accurately represent the salient physical processes governing ice–ship interactions. Nearly all past efforts on ice–ship physical modeling, numerical modeling, and full-scale trials have focused on the capabilities and design requirements for ice-capable ships. These ships have hull forms and steering and propulsions systems designed to operate in ice-covered waters. In contrast, existing U.S. Navy ships were designed to fulfill military requirements, such as speed, maneuvering, and seakeeping, in the absence of ice. Very few model tests

and no full-scale data are available to determine safe operational speeds for these ships in ice-infested waters. This report outlines an approach to fill this critical knowledge gap.

The proposed approach involves high-resolution physical experiments to quantify the forces generated during the ice–ship interaction processes relevant to safe operations and future design of Navy surface vessels in ice-covered waters. The proposed physical modeling effort will use the Cold Regions Research and Engineering Laboratory's (CRREL) refrigerated towing tank to conduct 1:5 scale impact tests of discrete ice floes against the stem and side panels of a triangular indentor. The impacts will be carefully controlled to obtain repeatable events across the range of hull angles and ice properties relevant for existing Navy ships in marginal Arctic ice. Instrumentation will measure impact locations and pressures, global forces and moments, ice deformation and rigid-body motions, and other key parameters. Importantly, the large scale factor will minimize scale distortions in hydrodynamics and ice properties; and it will allow high-resolution data and observations of the key impact processes.

A significant advantage of the proposed approach is that the physical model testing and numerical-model development will take place concurrently. Insights obtained from the physical testing can be immediately absorbed into the numerical modeling effort, and implications from the modeling can likewise inform the testing and validation effort. The results of this coupled physical-numerical modeling approach will enable the Navy to determine accurately, economically, and quickly the safe operating speeds for its existing ships across the range of marginal Arctic ice conditions in which it may be asked to operate.

1 Introduction

1.1 Background and motivation

The conditions in the Arctic are undergoing profound and rapid change with the summer ice extent exhibiting a steady decline. The summer minimum has decreased from approximately 7.5 million km^2 in 1979 to 3 million km^2 in recent years (Figure 1). This trend is expected to accelerate as the sea ice cover diminishes further because of the dramatic difference between the albedo (i.e., surface reflectivity) of ice (0.5 to 0.7) and open water (0.10). As the ice melts and is replaced by "dark" water, a significant portion of the incoming radiation is absorbed rather than reflected away as it was by the ice and snow cover. This leads to a positive feedback loop where the added radiative heat flux into the ocean leads to less or thinner (and "darker") ice, resulting in even more radiative heat flux (Serreze and Francis 2006; Screen and Simmonds 2010; Kumar et al. 2010). The result of this warming amplification is a severe acceleration in the Arctic ice cover decline, such that the Intergovernmental Panel on Climate Change (IPCC) projects that a nearly ice-free summer in the Arctic is likely to occur before mid-century (IPCC 2014).

Ice-free seasons will lead to significant changes in the activity level in the Arctic in the next 20 to 25 years as sea routes begin to open and ice conditions become less forbidding. The Office of Naval Intelligence projects over the next 5–10 years (through 2020–2025) that Bering Strait traffic will increase more than 100% and that the number of vessel traversing the Northern Sea Route, which tracks mostly along Russia's northern coast, will increase more than tenfold (Figure 2). A large proportion of this seasonal ice loss is projected to occur in the Chukchi and Beaufort Seas where the United States has sovereign interest and search and rescue obligations. The diminished ice cover will encourage an increase in ship traffic in the Beaufort and Chukchi Seas, coming mostly in the forms of ecotourism and energy extraction activities. A search and rescue response for either type of activity will test the capability of the U.S. Coast Guard (USCG) and may require the assistance of the U.S. Navy, in some instances.

Figure 1. The current sea ice extent record and model projections. The Arctic sea ice extent declined more than 60% during the satellite era (1979–present). The colored lines and shaded regions represent the sea ice extent predictions and variances for several Representative Concentration Pathways (RCP). RCP 8.5 represents a scenario with high greenhouse gas emissions and predicts an essentially ice free Arctic by 2060. Note that ice extents predicted under the RCP 8.5 scenario under predicts extent compared to observations for recent years (Melillo et al. 2014).

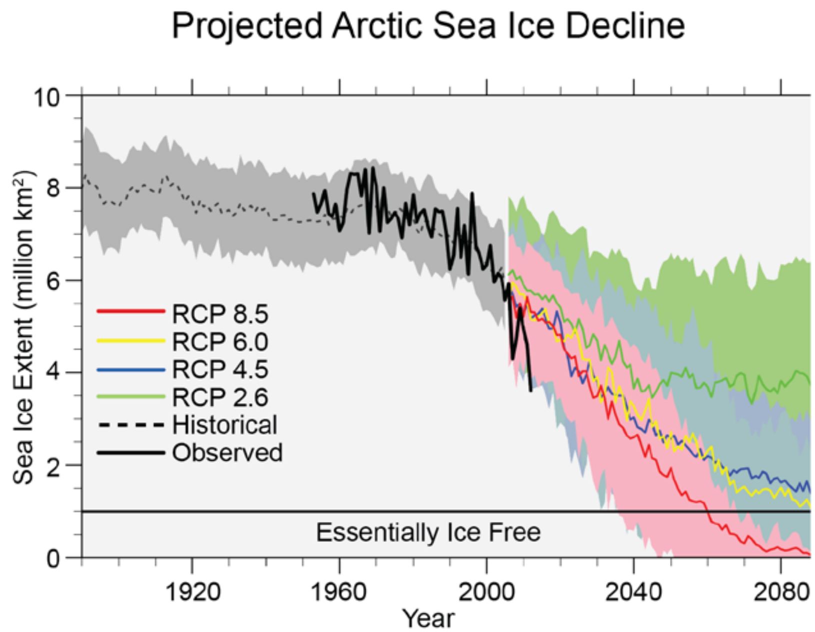
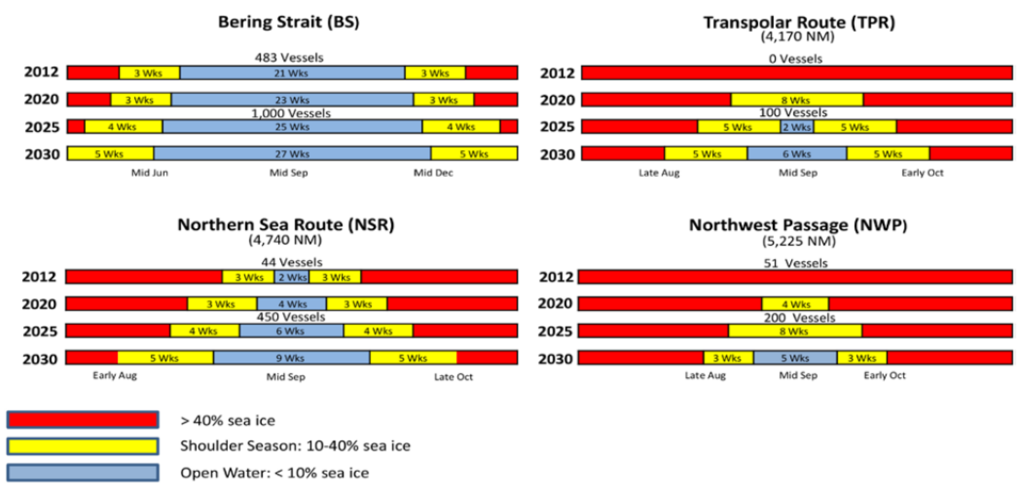


Figure 2. The predicted availability of Arctic transit routes from 2012 through 2030 (Navy Task Force Climate Change 2014).



Given the increased extent and duration of open water in the Arctic Ocean, there is a high probability that the Navy will need to operate in waters with partial ice cover ranging from 10% to 40%. This likelihood raises important questions: How well can existing Navy ships withstand intentional or accidental ice impacts? What are their safe speeds limits?

Accordingly, the Navy needs a tool to accurately estimate ice–ship impact loads to assess the risk to current vessels and to develop guidance for operation in ice covered waters.

1.2 Objective

To address the U.S. Navy concerns over the changing Arctic conditions and subsequent near-term (present–2020) to mid-term (2020–2030) action items outlined in the *U.S. Navy Arctic Roadmap 2014*–2030 (Navy Task Force Climate Change 2014), this report describes the current design guidance for ice-hardened ships and its theoretical underpinnings, the currently available physical testing facilities, and a physical modeling approach to bridge technical gaps in numerical ice-load models. The proposed physical modeling effort supports the U.S. Navy's strategic objective to provide ready naval forces to respond to crisis and contingencies in the Arctic.

1.3 U.S. Navy Arctic roadmap

Below are relevant near-term actions recommended in the U.S. Navy Arctic roadmap. The numbers in parentheses refer to specific action items in the Navy document (Navy Task Force Climate Change 2014):

> (2.1.10) Develop Arctic CONOPs [concepts of operation] for naval platforms and update as new capabilities are developed
>
> (2.2.5) Provide S&T [science and technology] plans for Arctic assessment and prediction to include:
> - Impact of Arctic environment on naval systems
> - Development of new technologies and adoption of existing technologies (e.g., sensors, platforms, and communications) for sustained operation and observation in the Arctic

> (2.7.2) Identify current capabilities of existing platforms to operate in open water (<10% sea ice) and shoulder seasons (<40% sea ice)
>
> (2.7.3) Identify future platforms and their engineering requirements that will operate in open water (<10% sea ice) and shoulder seasons (<40% sea ice) by mid 2020s
>
> (2.7.8) Evaluate requirements for sustainment of forces operating in the Arctic
>
> (2.7.10) Evaluate requirements for expeditionary units to conduct operations in the Arctic. Environments include on ice, ashore, on permafrost, under ice diving, littoral operations and construction including underwater construction in freezing/subzero conditions

Satisfactory completion of the action items described above will require further development of existing ice-impact force models, which are inadequate for U.S. Navy vessel hull forms and marginal ice conditions. These ice-impact force models require well-instrumented physical model or full-scale tests for numerical-model validation. At present, these data are rare for relevant hull forms and ice conditions relevant to future Navy Arctic operations, and the proposed effort is motivated by this lack of critical information.

2 Ice Impacts and Ship Design

The estimated level of ice-impact forces dominates the design of ships that intend to operate in ice-covered waters. These ships range from Polar Class icebreakers, whose roles include breaking channels through intact ice sheets and ice ridges, to ice-strengthened cargo ships and tankers, which generally operate in marginal ice, thin intact ice, or pre-broken channels. A major design goal for ice-capable ships is to minimize ice forces or to optimize hull strength for the given target ice thickness and strength to be encountered within an expected range of operating conditions. Design features such as shrouded propellers, rugged steering systems, and bow forms that promote flexural breaking of ice sheets and large floes enable safe and capable operation in ice-covered waters; however, these designs necessarily trade off open-water performance to maximize ice-capable performance.

In comparison, U.S. Navy surface ships are designed to maximize their military capabilities, which include open-water speed, maneuverability, and seakeeping. In contrast to ice-capable ships, Navy ships have fine bow shapes with near-vertical sides; slender, lightweight hulls; forward sonar domes; and unprotected rudders and propellers. Because of the near vertical hull angles for Navy ships, the peak forces on the hull will likely be controlled by ice crushing and momentum exchange rather than flexural failure, which dominates for ice-capable ships. Further, it will be important to understand the influence of ice on safe ship speed and maneuverability.

Additionally, Navy skippers have no experience operating their ships in ice and so have no context to inform decisions, such as whether they should strike ice floes stem-on to split them or whether they should maneuver around floes to avoid impacts but increase the risk of side-panel impacts. These considerations are minor for ice-capable vessels whose designs and operating guidance anticipate ice impacts but could prove catastrophic for thin-plated Navy vessels.

2.1 Classification rules and design guidance

Ship classification societies, such as ABS and Lloyd's Register, have collaboratively developed design rules and guidance to evaluate ship structural integrity and to advise safe operation mainly for actuarial purposes. As of the early 1990s, efforts have been made to standardize the classification of ice-capable ships.

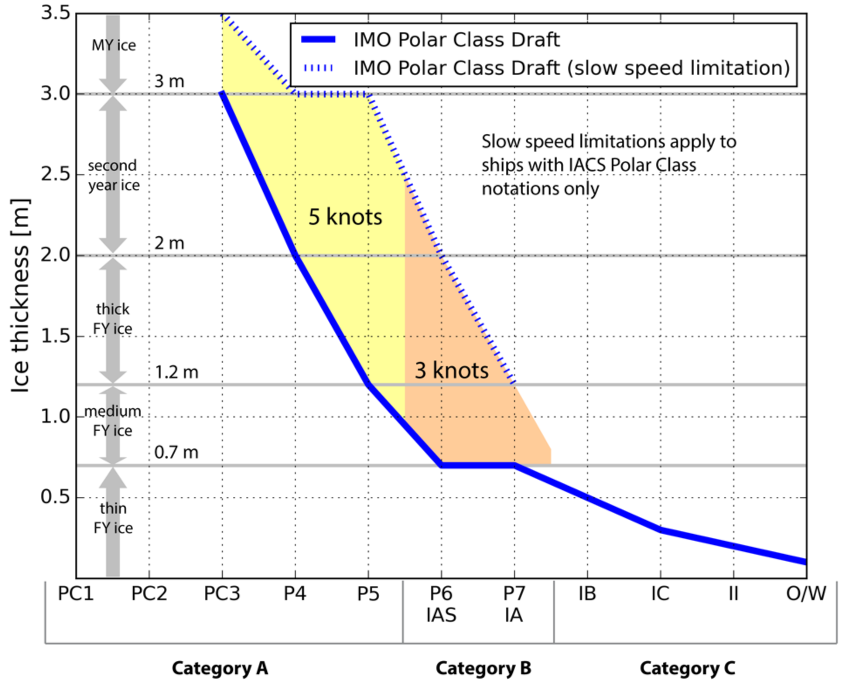
The International Association of Classification Societies (IACS) has produced the Unified Requirements for Polar Ships (Polar UR) operating in ice-covered waters (IACS 2011). The seven IACS Polar ice classes in this requirements document are defined using a range of hull-strength factors that determine a ship's ability to withstand ice forces for given ice conditions based on the World Metrological Organization (WMO) sea ice nomenclature (Figure 3). The Polar UR includes formulas developed to calculate ice forces and the resulting structural response to ensure that the hull design under consideration can endure the ice conditions associated with the requirements of each Class.

Figure 3. Classes of Polar ships. The Polar Class requirements are developed by the IACS and the Baltic, or Finnish-Swedish, Class requirements are developed by the Finnish and Swedish maritime authorities (after Reid et al. 2014)

Season	Summer/Autumn				Year Round				
Ice Type	First-Year						Second-Year	Multi-Year	All
Min Ice	0.15 m	0.25 m	0.35 m	0.5 m	0.7 m	1.0 m	1.3 m	1.8 m	3.0+ m
		Polar Class	PC 7	PC 6	PC 5	PC 4	PC 3	PC 2	PC 1
Baltic Class	IC	IB	IA	IA*					

The main concern of the Polar UR is the hull form design and strength required to operate in specific ice conditions, but it does not provide guidance for safe operations in these conditions (i.e., safe speeds). To address this gap in operational guidance for ice-covered conditions, the International Maritime Organization (IMO) has developed and proposed a Polar Operational Limit Assessment Risk Indexing System (POLARIS) that suggests a go/slow-speed/no-go decision for ship operators that is based on vessel speed, ice concentration, and ship classification (Figure 4). The POLARIS guidance derives largely from operational experience with ships in ice rather than the details of ice–ship interactions; therefore, there is room for significant improvements with improved understanding of ice-impact forces on various hull forms and ice conditions.

Figure 4. Speed limitations for level ice by ice class (after Canada et al. 2014).



2.2 Polar UR design guidance

The Polar UR specifically warns against broad application of its design guidance: "Design ice forces calculated according to [Section] I2.3.2 [in the IACS Polar Class requirements] are only valid for vessels with ice-breaking forms. Design ice forces for any other bow forms are to be specially considered by the member society." For instance, the Polar UR design scenario focuses on a glancing impact near the bow for determining the ship structure required to resist ice loads. The design ice load is assumed to be well characterized by an average pressure uniformly distributed over a rectangular load patch of height and width. In addition, the icebreaking hull forms are designed to encourage the flexural failure of the ice by producing a downward loading action. Therefore, the Polar UR assumes ship geometry and ice properties that may be appropriate for a classification system where worst-case load conditions drive design considerations but, for the case of Navy vessels, may not provide accurate load estimates crucial to developing safe-speeds guidance for a particular vessel and ice conditions pairing.

This section summarizes the technical approach underpinning the Polar UR, which is a combination of Popov collision mechanics (Popov et al.

1969) and empirically measured ice pressure–area relationships. This approach is fully detailed in Dolny et al. (2013), which includes an ice-load model and a ship structural response model. This report focuses solely on the ice-load model and its relevance to U.S. Navy surface vessels operating in ice-covered waters.

The design impact scenario used to establish ice-impact forces in the Polar UR is the case of a glancing impact between a ship's bow region and an ice floe of uniform thickness. The impact forces arise from momentum exchange between the ship and the ice floe through two modes of ice failure: (1) crushing or compressive failure, which dominates at low speeds, in thick ice, and in impacts with steeply angled hull forms, and (2) flexural failure, which dominates at high speeds, in thin ice, and in impacts with shallowly angled hull forms. The impact load calculations to be detailed below are based on a crushing-only mode of failure. Flexural failure is assumed to be catastrophic and therefore caps the calculated crushing-only impact loads.

The mechanics are based on the Popov collision model (1969) but are modified to include a wedge-shaped ice edge and a pressure–area ice indentation model. The ice–ship impact force is calculated by equating the normal kinetic energy to the ice crushing energy. The crushing energy is found by integrating the normal force over the penetration depth, as follows:

$$\frac{1}{2} M_e V_n^2 = \int_0^{\delta_{max}} F_n(\delta)\, d\delta \tag{1}$$

where

M_e = the effective mass of the ice–ship configuration,
V_n = the relative normal velocity at the impact location,
δ = the penetration depth,
δ_{max} = the maximum penetration depth, and
F_n = the hull-normal impact force normal at the impact location.

As interaction speed (kinetic energy) increases from zero, the design ice load follows the crushing mode calculation until the flexural-mode limit is reached. Because the flexural-failure stress is assumed to be independent of strain rate and hydrodynamic effects, the flexural limit in the Polar UR is independent of ship speed. Daley et al. (2011) proposed an extension to the flexural mode to account for hydrodynamic effects via a Froude number correction, which introduces a slight increase in failure load with increasing speed.

The normal impact force resulting from the crushing failure of ice is determined using empirical pressure–area relationships of the form

$$F_n(\delta) = P(\delta)A(\delta) \tag{2}$$

where the contact area is denoted as A and the contact pressure, P, is determined using an area-dependent power law, such that

$$P(\delta) = P_0 A(\delta)^{\gamma} \tag{3}$$

where P_0 and γ are fitting parameters.

Equation (3) links the average ice pressure and the ice–hull contact area. The justification for such a relationship has been the subject of numerous investigations for both ships (e.g., SSC 1990; Devine and Sodhi 1992; Daley 2007) and offshore structures (e.g., Sanderson 1988; Timco and Sudom 2013). In general, average ice-interaction pressures decrease as contact area increases during an impact, the so-called "spatial" or "local" pressure–area relationship. Theories have not satisfactorily established the appropriate form of the pressure–area relationship and its link to ice-failure processes. In addition, the loading function (or pressure–area relationship) is an empirical correlation to field and physical model data highlighted by dimensional inconsistency of Equation (3), which limits the generality of these relationships. The Polar UR assumes that $\gamma = -0.1$ and that P_0 varies with Polar Class to reflect ice-strength characteristic of the Class requirements.

2.3 Limitations of the Polar UR ice model for Navy ships

The assumptions and simplifications in the Polar UR ice model are supported by decades of operational experience with Polar Class ships in ice, and the empirical coefficients derive from extensive full-scale data. Because of the significant differences between icebreaking and Navy vessel hull forms, especially in the bow region, while satisfactory for Polar Class hull forms, this impact model may not accurately represent ice-interaction mechanics relevant to the hull forms of Navy ships operating in marginal ice cover. The following paragraphs summarize some key limitations of the Polar UR ice model and current research on ship–ice interactions as they pertain to Navy hull forms.

Ice rebound and impact forces. As described previously, Popov collision mechanics assume that ice crushing dissipates all of the effective kinetic energy of the impact. For ice-capable ships striking large floes or intact ice sheets, ice rebound may be small; and thus its omission introduces only minor conservatism. However, for Navy ships striking relatively small, isolated floes, ice rebound could be important; and thus the impact forces using Popov collision mechanics may be overly conservative (i.e., unrealistically large).

Inertial hydrodynamic effects. Because it anticipates collisions with large or intact ice sheets, the Polar UR ice model devotes little attention to inertial hydrodynamics effects (e.g., added mass). These effects are likely to be important for impacts with discrete ice floes at low concentrations. Added mass could vary substantially with floe size, shape, and lateral confinement for discrete ice floes.

Failure mode effects and equipment damage. The waterline bow forms of ice-capable ships are broad and rounded, and they provide shallow entry angles along the vertical centerline to promote downward ice breaking. The Polar UR thus anticipates glancing impacts near the bow. Navy ships, having fine, steep-sided bows, are likely to impact some ice floes stem-on. This could be beneficial: the stem is a strong structural location; splitting the ice floe would reduce forces relative to pure crushing, and rotational energy imparted from eccentric stem-on impacts would reduce ice-interaction energy. However, some Navy ships have bow-mounted appendages that could be vulnerable to impact by under-turned ice pieces. Also, maneuvering to avoid stem-on impacts raises issues of safe ship handling in varying ice concentrations. These issues are simply not addressed in the Polar UR or in the research that underpins it.

Applicable pressure–area relationship. For ice crushing, the Polar UR uses a simple pressure–area relationship based on data from ice-capable ships; and much research seeks to refine that relationship (e.g., Frederking 1999; Daley 2007; Timco and Sudom 2013). However, the steeper hull angles of Navy ships will likely delay the onset of flexural failure during an impact and thus will increase confining effects on ice-crushing mechanics.

Therefore, the resulting pressure–area relationship could be substantially different from that recommended in the Polar UR.

Multiple impacts. The relatively slender bow shapes with a gradual increase in beam with station that are characteristic of Navy ships increase the likelihood of multiple impacts of ice floes for each encounter. The Polar UR does not quantify effects of multiple impacts although some research has been conducted to provide design guidance for ice-capable ships (Daley and Liu 2010; Daley et al. 2014). Nevertheless, the locations and severity of multiple side-hull impacts warrants specific attention for Navy hull forms, as does the role of maneuvering on multiple impacts.

Tangential forces and friction effects. The Polar UR considers only normal forces resulting from ice impacts and does not include tangential forces arising from ice friction. Frictional forces could introduce important in-plane stresses during ice impacts for the thin hull-plating characteristic of Navy ships. Tangential forces and their variation with impact parameters thus warrant detailed investigation for Navy hull forms.

Stochastic considerations. The Polar UR does not cast its design guidance in a statistical framework although independent research offers several good methods to do so (e.g., Jordaan et al. 1993; Li et al. 2010; Kujala and Arughadhoss 2012; Suominen and Kujala 2014). The natural variability in ice properties yields important variations in predicted design loads. Conservative choices for the ice-related parameters can then lead to overly conservative design loads. Alternatively, a statistical formulation for ice-impact parameters can reduce conservatism to deliberately chosen levels (e.g., the largest load expected given 10,000 impacts). Furthermore, because ship speed affects ice-encounter frequency in partial ice cover, it has a direct influence on return-period statistics for ice-impact forces. Also, although maneuvering through low-concentration ice cover could reduce intentional ice impacts, it could also increase the risk of accidental impacts. That is, safe-speed and best-practice maneuvering guidance for Navy ships in ice must be cast in statistical terms.

Physical modeling can play a critical role in closing these knowledge gaps noted above for Navy ships. The focus, however, must be on understanding the physical processes that govern ice–ship interaction for Navy hull forms rather than traditional ice-capable hull forms.

3 Survey of Refrigerated Towing Tanks

Scaled physical modeling has a long tradition in naval architecture, including determining ice forces on ship hulls and appendages. Although ice simulants (e.g., made from foam, plaster, etc.) have been used in scaled model testing, a common approach for work conducted in refrigerated facilities is to grow ice with strength properties that are reduced according to a scaling law. Because of corrosion problems with salt water in such facilities, various non-corrosive dopants (e.g., urea and ethanol) are introduced to achieve the desired strength reduction. In addition to the model ice type used at a particular facility, other key parameters distinguish the existing refrigerated tank facilities, including, but not limited to, the tank dimensions, the temperature range, and the testing speed range.

The scaling requirements for physical model testing are described in the next subsection followed by a summary of key challenges and differences between the different model ice types and concluding with a global overview of the current refrigerated towing tank facilities with brief descriptions of their capabilities.

3.1 Scaling requirements

Standard practice for ice–ship interaction tests requires application of Froude and Cauchy scaling laws (e.g., Tatinclaux 1988) to preserve the ratios of inertial and strength forces, respectively, to gravitational ones:

$$F = V/\sqrt{gh} \tag{4}$$

$$C = \sigma/\rho g h \tag{5}$$

where

F = Froude number based on ice thickness,
V = speed,
g = gravitational acceleration,
h = ice thickness,
C = Cauchy number based on ice thickness,
σ = ice strength,
E = elastic modulus, and
ρ = water density.

The geometric scale factor, λ, is defined as a ratio between length scales, denoted here as L, giving the scale factor the form $\lambda = L_p/L_m$, where the subscripts p and m refer to prototype (full-scale) and model values, respectively. Setting $F_m = F_p$ and $C_m = C_p$ establishes the scaling requirements for most of the scaled model test parameters:

$$V_p/V_m = \lambda^{1/2} \tag{6}$$

$$h_p/h_m = \sigma_p/\sigma_m = E_p/E_m = \lambda \tag{7}$$

Consistent with ice–ship model tests, an ice-impact test should seek to preserve dimensionless ratios related to buoyancy forces, ice–hull friction, and ice elastic deformation:

$$(\rho_i/\rho)_m = (\rho_i/\rho)_p \tag{8}$$

$$f_m = f_p \tag{9}$$

$$(l_c/h)_m = (l_c/h)_p \tag{10}$$

where

ρ_i = ice density,
f = ice–hull friction coefficient, and
l_c = ice characteristic length (related to elastic modulus and ice thickness).

Faithful adherence to either Froude or Cauchy scaling is not always possible because of the unique structure of ice where the tensile and compressive strengths of ice do not scale isotropically with ice thickness. This leads to scale distortion that complicates the extrapolation of scaled model behavior to the full-scale performance. The cost of controlled full-scale tests, however, can be prohibitive; and measurement of the ice parameters can be difficult. Therefore, scaled physical modelling is typically the most economical and useful option. Careful control of the model ice properties (through control of its microstructure) and using a model scale that is as close to full scale as is feasible are the most important ways to minimize the effects of scale distortion.

3.2 Model ice formulations

Physical model tests require that model ice properties scale in relation to the target full-scale values according to the scale factor chosen for the linear dimensions of the ship model (e.g., 1:20 scale). The two main scaling laws are Froude scaling, which preserves the ratio of gravitational forces to inertial forces, and Cauchy scaling, which preserves the ratio of elastic or strength forces to inertial forces. Taken together, these two scaling laws dictate that ice thickness, failure stresses, and elastic modulus scale linearly with the model scale factor. In addition, to preserve the relative importance of buoyancy and frictional forces, model ice density and the friction coefficient should remain the same as the corresponding full-scale values. If any of these scaling requirements are not satisfied, scale distortions will result with varying effects on the accuracy of the model results when projected to full scale.

The above scaling requirements pose two major challenges. The first challenge is to understand the material behavior of sea ice in compression, flexure, shear, and tension. This is not a small task. For instance, the flexural strength of sea ice is a function of brine volume, which is a function of temperature and salinity (Timco 1986). In addition, ice in the field forming under natural conditions is anisotropic and may be heterogeneous, with pores, flaws, cracks, and other weaknesses affecting its strength (Jordaan 2001). Timco and Weeks (2010) listed the state of knowledge for first year ice as “Good” for flexural and compressive strength, “Limited” for tensile strength, and “Poor” for shear strength and friction.

The second challenge is to select or design a model ice to match the scaled material behavior of the target full-scale ice. Because of the effort required to achieve consistent and reliable model ice properties, ice tank operators develop and champion (even patent) their own particular type of model ice.

There are two broad classes of model ice microstructures used in refrigerated tanks: columnar model ice and granular model ice. Specific types of columnar ice include saline ice, urea-doped ice, ethanol-doped ice, or ice containing a combination of dopants, with a mixture of ethylene glycol, aliphatic detergent, and sugar (commonly referred to as EG/AD/S ice) being the most common. Sea ice in nature has a primarily columnar structure (Lainey and Tinawi 1984), and columnar model ice has the benefit of replicating this structure. Numerous techniques have been developed to tune the density, strength, or homogeneity of columnar model ice, including adjusting the concentration of dopants, adding air bubbles during freezing, and tempering (i.e., warming the ice after growing it to the desired thickness).

Granular model ice is made by spraying saline water at appropriately low temperatures, resulting in a fine-grained model ice referred to as FG or FGX model ice. The FGX is an improved fine-grain model ice that differs in salinity from FG ice. Another type of granular ice is made by spraying an ethanol solution (resulting in granular ethanol [GE] model ice) and accumulating the ice layers. In general, the disadvantage of granular model ice is that the compressive strength is low and the fracture toughness is high (Lau et al. 2007) relative to the columnar microstructure.

Compressive strength and flexural strength must be scaled correctly to model the crushing and bending failure modes, respectively, in the target full-scale ice. Downward bending failures limit ice forces during ice–ship interaction for ice-capable hull forms, particularly at higher ship speeds. Most ice tanks, therefore, seek to scale flexural strength as their primary strength value; and most model ices meet the flexural-strength criteria for scaled sea ice (Lau et al. 2007). Nevertheless, preserving the ratio of flexural strength to crushing strength is important for scaling the transition between these modes, which could be particularly important for Navy ships where full-scale observations of ice impacts are essentially non-existent. As Figure 5 shows, most model ices can scale compressive strength relative to flexural strength, in part owing to the large range of variability in full-scale sea ice.

Because the ice experiences a complex stress state during ice–ship interaction, defining the stress levels at which the ice yields for any combination of compressive and tensile stress states (i.e., a "failure envelope") may be appropriate. Figure 6 shows a comparison of the failure envelopes of urea model ice and EG/AD/S model ice with respect to columnar sea ice (Timco 1986). EG/AD/S ice performs better than urea ice in matching the sea ice failure envelope. However, this performance comes at much higher cost compared to other model ices, such as those doped with urea.

Figure 5. Model ice compressive strength versus flexural strength compared to scaled sea ice (*shaded area*) (after Lau et al. 2007).

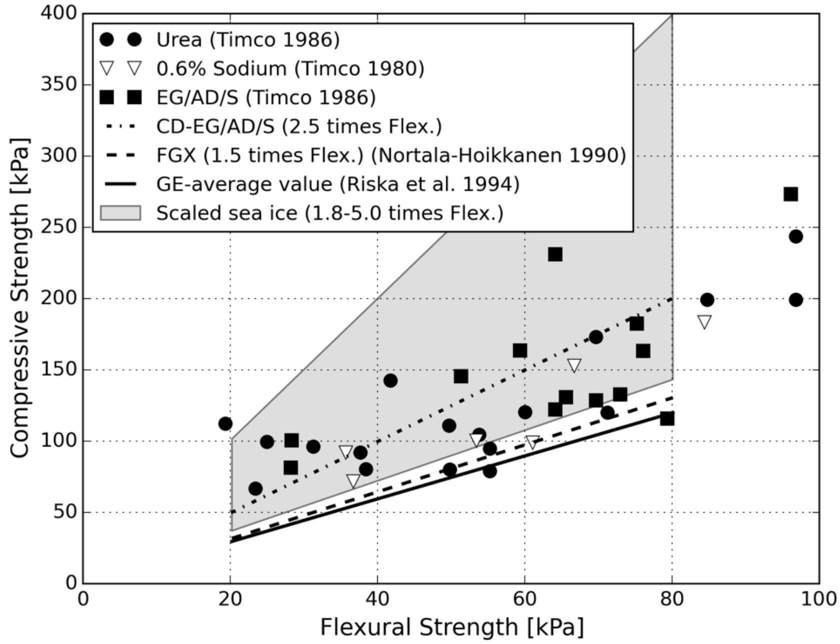
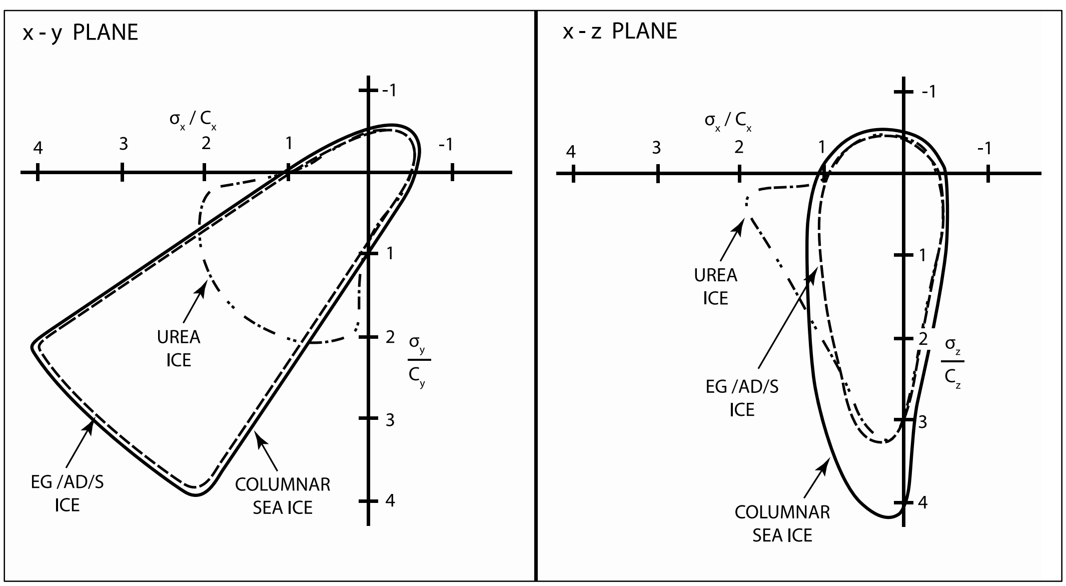


Figure 6. Differences in the size and shape of the full failure envelope affect the interpretation of experimental results (after Timco 1986).



Other distortions in model ice mechanical behavior include the high residual plasticity resulting from a low ratio of Young's Modulus to flexural strength, the higher impact forces resulting from fracture toughness that is too high (and thus delays floe splitting), and the error stemming from the dependence of fracture toughness and compressive strength on strain rate. Again, because full-scale sea ice displays large variability in mechanical properties, some scale distortion is generally acceptable in ice–ship model studies. Post-test statistical analyses can then be used to account for this variability to forecast expected design forces. To complicate matters further, the fracture mechanics that govern splitting and flexural failure is likely to be scale dependent, which would in turn introduce an additional source of scale distortion.

The Cold Regions Research and Engineering Laboratory (CRREL) uses urea model ice in its studies. The advantages of urea ice are that it is not corrosive, the formulation is comparatively simple and inexpensive, and it has the columnar microstructure of naturally occurring sea ice. In addition to the proper crystal structure, urea doped ice contains distributed liquid inclusions similar to the characteristic brine inclusions of sea ice (Hirayama 1983); and its strength has the appropriate size scaling (Gow 1984). In addition, the repeatability of the structure and strength properties of urea doped ice sheets is good. For the CRREL tank, Borland (1988) judged urea model ice favorably compared to EG/AD/S in terms of flexural properties. One disadvantage of urea model ice is the low ratio of Young's modulus to flexural strength for thin, weak ice sheets. Tatinclaux (1988) warns against using urea ice sheets with a thickness less than 2 cm or ice flexural strengths less than 20 kPa. Another disadvantage is the two-layer structure of urea model ice, which results from seeding the water with sprayed ice crystals before growing the columnar ice. There is a noticeable difference in strength between the seeded and columnar layers (Tatinclaux 1988; Hirayama 1983). Fortunately, both of these disadvantages can be mitigated through experimental design or model ice growing procedures. In fact, the thickness of the granular layer has been reduced to less than 10% of the total ice thickness (Gow 1984). Urea model ice can reproduce a wide range of ice properties, and larger scale factors (larger than 1:20) can minimize scale distortions.

3.3 Current ice testing facilities

Refrigerated towing tanks have supported the design of ships and offshore structures designed to operate in ice-covered waters and can provide valuable information about ice–structure impact and interaction forces. The first ice tank was built in 1955 at the Arctic and Antarctic Research Institute in Russia, followed by three ice tanks in Finland, Germany, and the United States in the next two decades. By 1985, ten more tanks were built worldwide. Tatinclaux (1988) reviewed the early history of these tanks in more detail.

Arctic oil and gas exploration declined during the 1990s and into the 2000s, and half of the world's ice tanks closed. However, the reduced minimum extent of the Arctic sea ice and economic conditions that justified the cost and risk associated with Arctic energy extraction (conditions that have since changed) lead to a marked increase in energy exploration activities and associated vessel traffic through the Arctic Ocean. This economic activity has prompted renewed interest in the physical modeling of ice–ship and ice–structure interactions to the level where South Korea (in 2010) and Russia (in 2014) invested in two large refrigerated towing tanks. Activity at existing tanks has increased: Aker Arctic has reported almost double the number of test days per year in 2008 and 2009 versus the previous 15 years (Aker Arctic Technology Inc. 2009). In addition, Australia, Canada, China, Finland, India, Norway, Russia, and Britain all have plans to build or acquire new icebreakers, which will require physical modeling to develop and validate their designs.

Table 1 lists the principal ice tanks currently active in the world, along with their dimensions and ice-making characteristics. These ice tanks support a variety of design and operational activities, including ship resistance, maneuvering and propulsion, local and global ice–structure interaction forces, and ice management.

Table 1. Operational refrigerated towing tanks listed by host organization.

Host Organization	Location	Start Year	Length (m)	Width (m)	Depth (m)	Speed Range (m/s)	Min Temp (°C)	Ice Thickness (cm)	Ice Type
CRREL	Hanover, New Hampshire, USA	1978	37	8	2.4	0.3–2.2	−24	2–15	Urea doped
National Research Council of Canada (NRC-C)	St. John's, Newfoundland, Canada	1985	90	12	3	0.0002–4	−30	0.5–28	EG/AD/S
National Research Council of Canada (NRC-C)	Ottawa, Ontario, Canada	1980	21	7	1.2				EG/AD/S
Hamburg Ship Model Basin (HSVA)	Hamburg, Germany	1984	78	10	2.5/5.0	0.001–3	−20	1.5–20	Urea doped
Aalto University	Helsinki, Finland	1988	40	40	2.9	0–3	−25	7	GE
Aker Arctic Technology Inc.	Helsinki, Finland	2005	75	8	2.1	0–3			Saline FG/FGX
Korea Research Institute	Daejeon, South Korea	2010	42	32	2.5				EG/AD/S
Krylov State Research Center	St. Petersburg, Russia	2014		10	1.75	0.0005–1.2	−32	1–10	Saline FG

Each tank configuration offers specific modeling advantages and limitations. Long, large tanks provide important benefits when testing full ship models in level ice. In particular, large tanks allow ship models to be tested at larger scale factors (to reduce effects of scale distortion), at higher speeds, and for longer durations at each speed interval. The longer test duration increases confidence in the forces statistics given the unsteadiness in the icebreaking process. Wide tanks can accommodate a greater number of test channels per ice sheet to obtain more data for the same refrigeration costs (i.e., one ice-sheet growth cycle). The wider tanks can also support full-turning ship maneuvering tests. The larger tanks, however, require much larger cooling capacity; and typically, only large, well-funded, efforts justify their use. In contrast, smaller tanks operate economically and can accommodate a diverse set of experiments in shorter spans of time, often with a focus on details of the ice–structure interaction process.

All facilities still actively pursue fundamental research for ice–ship interaction, often using smaller secondary tanks to reduce costs. This research seeks to answer the many open questions concerning the prediction of a ship's performance in ice, including the physics of the ice-impact process itself. For instance, considerable research continues to investigate the details of ice-induced forces on ship hulls, including time-dependent patterns of contact and pressures, modes of ice failure, and the pressure–area curve used to aggregate the crushing phenomenon for design purposes. The Aalto Ice Tank (Suominen and Kujala 2014; Kujala and Arughadhoss 2012), Aker Arctic (Määttänen et al. 2011), the National Research Council-Canadian Hydraulics Centre (Frederking and Timco 2000), the National Research Council Institute of Ocean Technology (Gagnon 2004; Manuel et al. 2013; Daley and Colbourne 2014), the Hamburg Ship Model Basin (Karna et al. 2010; Lubbad and Løset 2011), and CRREL (Sodhi 2001a) have all been used to investigate the physics of ice-impact forces. Additional studies have sought to match model impact tests with full-scale field trials to assess modeling accuracy (Johnston and Gagnon 2005; Devine and Sodhi 1992; Kujala and Arughadhoss 2012). This basic research across the tanks reveals that fundamental questions about impact loads during ice–structure interaction have not been adequately answered.

3.4 Specific tank activity relevant to ice impacts on ships

This section summarizes research concerning ice mechanics relevant to ice impacts on ships along with brief descriptions of the major ice tank facilities organized by country.

3.4.1 Finland

The Finnish-Swedish Ice Class Rules, which have their origin dating back to 1890, are considered by some to be the industry standard for designing ships for first-year ice environments (Riska and Kamarainen 2011). The Aalto University Ice Tank has continued this work by addressing conditions encountered in first-year ice in the Baltic Sea (Kujala et al. 2007; Kujala and Montewka 2014). In addition, Riska and Kujala led a group of researchers interested in the statistical distribution of short-term ice-induced loads on a ship's hull (Suominen and Kujala 2014) and the statistical analysis of ice-crushing pressures on a ship's hull (Kujala and Arughadhoss 2012). There were also efforts to validate dynamic ice loading in numerical models (Zhou et al. 2013). Of particular interest are a series of studies exploring accidental collision scenarios (Kim et al. 2012; Kim 2014). The research focus and techniques used may provide some guidance for the ice–hull interaction relevant to Navy ships.

As the world's only privately owned ice model testing facility, Finland's Aker Arctic Technology has a decidedly commercial focus (Aker Arctic Technology Inc. 2015). While the current ice basin was inaugurated in 2006 (Wilkman et al. 2010), Aker Arctic and its predecessor Wartsila Arctic Design have extensive experience in physical ice-model testing over the last 40 years. Highlighting the community's ongoing need to validate model results with full-scale ship trials, Aker Arctic has completed over 200 full-scale field tests and expeditions.

3.4.2 Germany

The Hamburg Ship Model Basin (commonly referred to as HSVA) has two refrigerated towing tanks: the Large Ice Model Basin and the smaller Arctic Environmental Test Basin. HSVA has been active in both commercial testing of ships and structures in ice and research to advance the state of understanding of loads due to ice interaction with offshore structures. A recent research thrust has been the Dynamic Positioning in Ice (DYPIC) (Jenssen et al. 2012), which spans relevant topics such as the influence of ice concentration on ship hull impact loads in a managed ice field (van der Werff et al. 2012), the effect of ice drift on moored dynamically positioned structures, modeling efforts to predict ice drift (Haase and Jochmann 2013), and advances in classifying ice concentrations from optical tracking (Zhang et al. 2015).

3.4.3 Canada

Canada hosts two active refrigerated ice tanks, both operated by the National Research Council of Canada (NRC-C). The smaller Canadian Hydraulics Center (CHC) ice tank has investigated impact forces, floe accelerations, and local pressures produced by ice floes of various shapes and sizes on a large-scale structure (Frederking and Timco 2000). At the Institute for Ocean Technology (IOT), where the larger tank resides, small glacial ice masses were impacted with a plate simulating a ship's bow. A novel pressure panel installed at a near-bow impact location allowed researchers to observe and measure the evolution of the contact area and pressure. This study showed that peak load depended on impact speed, not on the duration of impact (Gagnon 2004).

The IOT has also conducted physical and numerical modeling to determine ice loads in managed ice conditions for dynamically positioned vessels (Millan and Wang 2011). Dolny et al. (2013) cast the Polar UR ice model in a form to demonstrate its use to determine safe operating speeds for ships in ice, and (Daley and Liu 2010) investigated mid-body impacts versus glancing impacts at the bow.

3.4.4 Russia

The ice tank at Russia's Krylov State Research Centre began operations in 1986 and was enlarged and inaugurated in 2014 as the world's longest at 102 m. Karulin and Karulina (2010) performed model tests with discrete ice floes for an ice concentration of 80% to validate numerical simulations of the ice loads on a moored tanker.

3.4.5 South Korea

As of 2007, South Korea owned 43% of the world's market share in shipbuilding (Lee et al. 2007) and has recently invested in a new ice tank (KORDI 2011). Recent publications from this facility have focused on tuning the model ice (Cho et al. 2010) and on optimizing experimental procedures (Cho et al. 2013). The 2013 Annual report (KIOST 2014) cites a desire to develop guidelines for safe operation of ice-class vessels on the Arctic Sea Route.

3.4.6 United States

CRREL operates the only remaining refrigerated ice tank in the United States. Testing activities have included ship-model testing for hull and propulsion performance (Tatinclaux 1988, 1989, 1992) and ice–structure interaction research (Sodhi 1998, 2001a). In 1992, CRREL worked with the Naval Surface Warfare Center to conduct scale-model ice-impact tests on a conceptual navy frigate to characterize local loads (Devine and Sodhi 1992). This test program varied ice thickness, floe diameter, and floe shape in addition to ship class, speed, and type of impact. The study provided a unique contribution to the field as one of the few ice-model tests of typical navy hull forms. Recently, CRREL worked with the USCG to investigate the range of ice conditions in which they could operate small, non-ice-hardened vessels and were specifically interested in the capabilities of propulsion systems (Haskins et al. 2014).

4 State of Knowledge of Ice Impacts on Navy Hull Forms

The U.S. Navy has not previously operated surface ships in the Arctic because historical ice conditions have limited surface-vessel access. Consequently, very few studies exist that seek to quantify ice forces on Navy hull forms.

Devine and Sodhi (1992) conducted physical model tests in CRREL's test basin on 1:19 scale models of the USCG *Polar Sea* and a conceptual naval frigate. Installed along the bow of each model was a custom-made pressure-sensing panel, and the model was towed into individual ice floes such that impacts occurred on the panel. A load plate at the model-carriage mount measured horizontal forces, and video cameras above and below water documented the impacts. The dataset included 72 impacts on the *Polar Sea* model and 186 impacts on the conceptual frigate model. The authors analyzed each impact to obtain the time sequence of pressure–area curves and best fit the maximum pressure–area curve.

For the *Polar Sea* model, Devine and Sodhi (1992) compared maximum pressures predicted from tests involving smaller floes (1.5 m diameter model scale or 29 m diameter full scale) with results derived from full-scale trials of the *Polar Sea* conducted in the Bering Sea marginal ice zone in 1986. The model predictions overlapped the full-scale results but showed wide scatter and generally higher pressures (Devine and Sodhi 1992). The authors did not provide comparable analyses for the conceptual frigate versus the *Polar Sea* full-scale data, but the pressure–area equations for the frigate model also showed wide scatter. They suggested that the model results could form the basis for statistical simulations using Monte Carlo methods.

Many ice-capable ships have been instrumented to measure ice-impact forces during full-scale trials. Particularly well analyzed are data from the *Polar Sea* (Daley et al. 1984; SSC 1990; Jordaan et al. 1993; Daley 2007), the Canadian Coast Guard icebreaker *Sir John Franklin* (Williams et al. 1992; Spencer and Jones 2001), and the USCG *Healy* (Sodhi 2001b; Jones et al. 2001; Santos-Pedro and Timco 2001). These analyses were used to validate physical modeling methods (e.g., Tatinclaux 1988; Tatinclaux 1989; Colbourne and Lever 1992; Tatinclaux et al. 1992; Jones 2004) and provide insight into the mechanics of ice–ship interaction. As noted, however, the hull forms of icebreakers differ substantially from those of Navy ships, so existing full-scale data cannot be used directly to develop guidance for impact loads and safe speeds for Navy ships in ice. The team is unaware of any full-scale trials of Navy surface ships in ice.

Researchers have undertaken laboratory studies of ice impacts with flat plates that provide insight into likely interactions of ice with Navy hull forms (e.g., Sodhi 1998; Sodhi et al. 1998; Gagnon and Bugden 2008; Kim et al. 2013, 2014). Most of these studies have focused on ice impacts perpendicular to the flat plate, which is more characteristic of ice impacts with vertical-sided offshore structures than glancing impacts on ships. However, Riska (1991) combined laboratory and full-scale observations to demonstrate that ice crushing due to ice–ship interaction can display high contact pressures along a line-like region, a failure mode also characteristic of thin ice crushing against a flat plate. Such laboratory investigations reproduce the salient features of large-scale behavior and could form the foundation for a generalized theory of ice–ship impact mechanics.

To date, numerous theories have been formulated to account for non-simultaneous failure and local splitting and spalling along the crushing face (e.g., Daley et al. 1998; Jordaan 2001). These theories are still actively under development, and no clear consensus exists for basic issues such as whether a scale effect exists in pressure–area curves (Sodhi 2001a).

Laboratory studies of ice crushing have benefited from the development of tactile pressure sensors that can measure local ice pressures over small areas (a few square centimeters) and high sample rates (up to several kHz) (e.g., Sodhi et al. 1998; Izumiyama et al. 1998, 1999; Lu et al. 2013; Lu et al. 2014). These tactile sensors enable the spatial distribution of ice pressures to be measured through an impact, which in principle allows analysis of pressure, force, and pressure–area statistics suitable for design purposes.

Despite significant research activity on ice–ship and ice–structure interaction, the likely impact locations, peak forces, and peak pressures for Navy ships transiting marginal ice zones are essentially unknown. The roles of hull shape, speed, maneuvering, and ice size and strength have not been systematically studied for characteristic Navy hull forms. The need to address these critical knowledge gaps has prompted the research program described below.

5 Large-Scale Model Tests

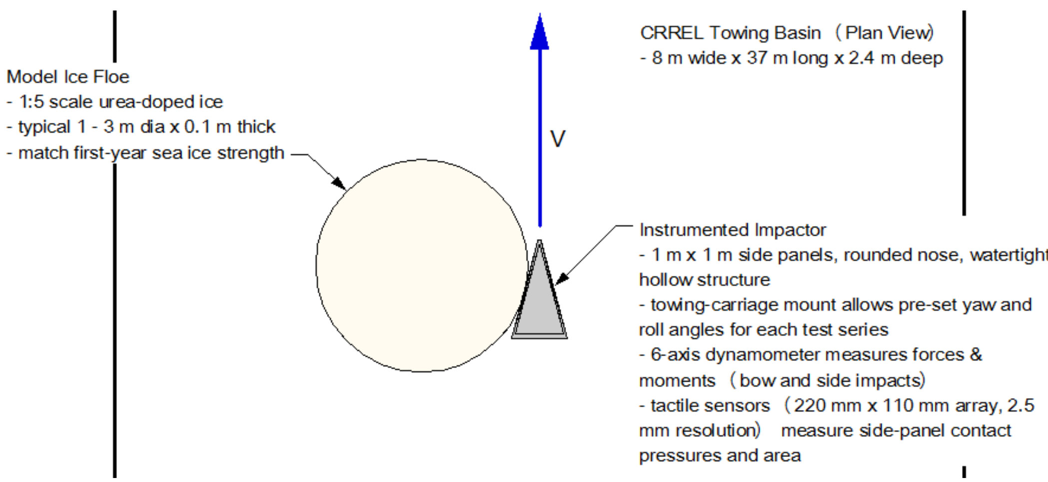
This section describes proposed CRREL physical model tests of ice–ship impacts relevant to U.S. Navy ships.

5.1 Rationale and approach

The details of ice–structure interaction vary significantly with ice properties, impact geometry, and rates of interaction. Interactions most relevant to the safe transit of existing U.S. Navy vessels through Arctic ice involve vessel stem and side-panel impacts with individual, mainly first-year, ice floes. Within this category of interaction, the magnitude and spatial distribution of peak pressures are of greatest interest to predict structural damage and thereby establish upper bounds for safe transit speeds.

CRREL proposes conducting a series of 1:5 scale ice-impact tests in its refrigerated towing tank. The tests will document an instrumented impactor interacting with discrete, floating ice floes. Figure 7 shows a schematic of the test layout.

Figure 7. Schematic (plan view) of the proposed large-scale ice–hull impact experiment to be conducted in CRREL's refrigerated towing basin. Shown here is a side-panel impact.



Although similar in shape to a ship bow, the impactor will not be a scaled ship model. Rather, it will consist of flat panels and a rounded nose to facilitate carefully controlled side-panel and stem impacts across a range of impact angles. Large-scale ice modeling will maximize experiment fidelity by minimizing scale distortion of ice properties (crushing strength, flexural strength, density, etc.) and by preserving important hydrodynamic effects (added mass, viscous effects, and buoyancy forces). It will also permit high-resolution acquisition of key impact data (spatial distribution of contact pressures, global interaction forces, ice-floe failure modes, floe momentum change, etc.).

5.2 High-resolution data

The instrumented impactor will be structurally stiff and rigidly mounted to the main towing carriage. The impactor–carriage mount will include a six-axis dynamometer to measure global forces and moments during impacts. One side panel will include face-mounted tactile sensors (220 mm wide × 110 mm high with 2.5 mm spatial resolution) to record the spatial distribution of pressures during impact. The data acquisition rate will be 100 Hz per channel with 16-bit resolution.

The experiment design will allow CRREL to adjust and control the impact geometry (Figure 8). The impactor wedge will have a 30° included angle between vertical, 1 m^2 side panels. The-carriage mount will have adjustments to preset the yaw, roll, and pitch angles. An actuated brace will hold the ice floe in position until just prior to impact to ensure that side impacts occur on the tactile sensors and bow impacts have preset eccentricity. The tests will manually position the ice floe against the impactor to achieve these settings before backing away the carriage to initiate the impact test.

High-speed digital video cameras will record the impacts (at a frame rate of at least 100 Hz). One camera will capture details of ice crushing and spalling at the impact zone, and two separated cameras will track the global motion of the ice floe and record fractures occurring away from the impact zone (radial and circumferential cracks). An underwater camera will record the impact events from below. The team will synchronize these recordings with the sensor-data time series.

Motion-tracking software will use the stereoscopic video recordings to determine ice-floe global motions resulting from impacts. In addition, a lightweight, waterproof inertial package will mount on the ice floe to record six-axis accelerations and angular rates. The inertial package will provide high-resolution motion data for the ice floe (at least until the floe splits) while the motion-tracking system will record the global motions of all large ice pieces, including overturning of fractured pieces against the impactor.

Figure 8. Variations in ice–hull impact geometries: (*left*) carriage mount allows preset yaw (*Y*) and roll angles for side-panel impacts; (*right*) carriage mount also allows preset stem (pitch) angles for bow-on impacts. An actuated brace (not shown) will hold the ice floe in position until just prior to impact to ensure side impacts occur on tactile sensors and bow impacts occur with preset eccentricity (*E*).

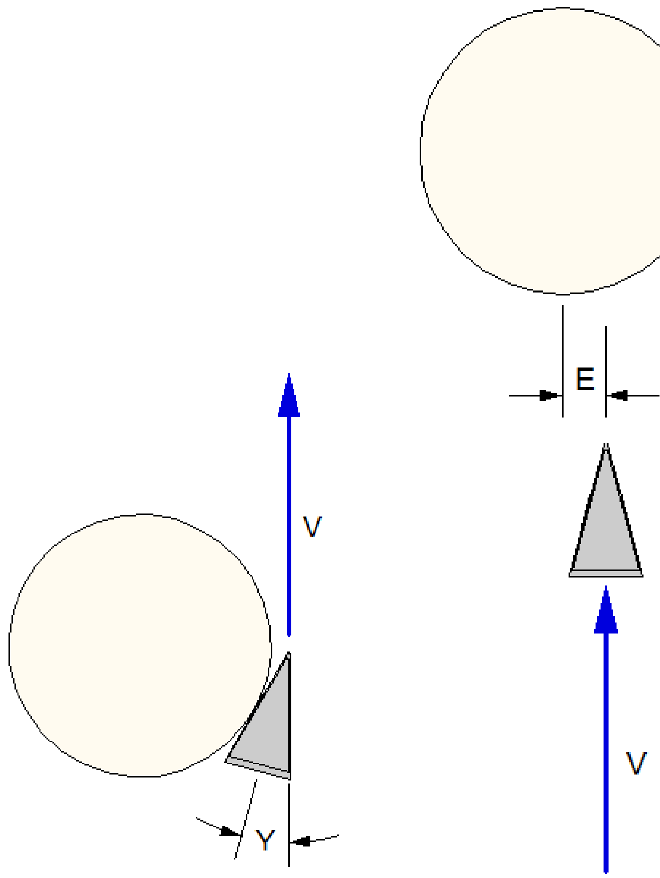


Table 2 summarizes the scaling laws and resulting parameters ranges for the proposed ice-impact tests conducted at $\lambda = 5$. Note that CRREL's Ice Towing Basin can accommodate a broad range of conditions of interest. The towing carriage can achieve equivalent full-scale impact speeds up to 4.9 m/s (9.6 knots). The 8 m wide basin can accommodate ice floes up to about 4 m in diameter (20 m full scale) with the impactor offset to one side of the carriage and can test model ice thickness up to 0.2 m (1 m full scale). Urea-doped ice at $\lambda = 5$ can satisfy scaling requirements for first-year ice material properties.

Table 2. Parameter ranges for 1:5 scale ice–hull impact tests based on Froude scaling. Subscripts p and m refer to prototype (full scale) and model properties, respectively.

Parameter	Ratio	Scaling Law	Scale Factor	Prototype Range		Model Range	
Froude no, $F = V/(gh)^{1/2}$	F_p/F_m	1	1	0.30	1.6	0.30	1.6
Cauchy no, $C=\sigma/\rho gh$	C_p/C_m	1	1	82	82	82	82
ice thickness, h (m)	h_p/h_m	λ	5	0.5	1	0.1	0.20
velocity, V (m/s)	V_p/V_m	$\lambda^{1/2}$	2.24	0.7	4.9	0.3	2.2
density ratio, ρ_i/ρ	$(\rho_i/\rho)_p/(\rho_i/\rho)_m$	1	1				
elastic modulus, E (GPa)	E_p/E_m	λ	5	1.7	3.7	0.34	0.74
flexural strength, σ_f (kPa)	$\sigma_{f,p}/\sigma_{f,m}$	λ	5	400	800	80	160
compressive strength, σ_c (kPa)	$\sigma_{c,p}/\sigma_{c,m}$	λ	5	1600	3200	320	640
time (s)	T_p/T_m	$\lambda^{1/2}$	2.24	0.1	1	0.04	0.45
Output Variables							
pressure (kPa)	P_p/P_m	λ	5	100	10,000	20	2000
area (m^2)	A_p/A_m	λ^2	25	0.1	3	0.004	0.120
force (kN)	F_p/F_m	λ^3	125	50	5000	0.4	40

5.3 Test procedures

Prior to each test series, CRREL will grow model ice floes of the target thickness, diameter, and mechanical properties. This involves cooling the urea-doped water, seeding a top layer of ice crystals, allowing the ice to grow several hours to the requisite thickness, and warming the room to temper the ice slowly while periodically measuring flexural strength in situ. While the ice sheet is tempering, the team will cut it into circular floes of the desired sizes and clear away the surrounding ice (as seen in Figure 9). When the ice reaches its target strength, the impact tests will begin.

Figure 9. Ice-impact test conducted in CRREL Ice Towing Basin on conceptual navy frigate (Devine and Sodhi 1992). A custom-made pressure-sensing panel (*white box*) recorded local pressures at the ice–ship contact area (image courtesy of U.S. Navy).

As noted above, the team will manually position a floe to contact the impactor at the desired location (stem or side-panel tactile sensors) and restrain it using an actuated arm. Then, the team will back away the towing carriage, initiate data acquisition, and drive the carriage forward to impact the floe at the desired speed. The restraining arm will release the floe just prior to impact. The team will inspect the ice floe for damage and failure mode, store the test data, and repeat the tests for each available ice floe. The entire test series will span a ranges of floe size, ice strength, impact speed, and ice–hull impact geometries (Table 2), with replicates at each combination to assess consistency.

The analysis of the test data will be conducted with the eventual numerical modeling and validation objective in mind and will focus on determining the energy and momentum exchanges, impact force, impact pressure levels, impact durations, ice failure modes and sequences, and post-impact ice floe motions. The team will archive the raw and processed data for each test, including narrated video to provide a visual summary of each impact.

5.4 Cost estimate and schedule

Table 3 outlines a series of tasks and associated costs that compose the physical modeling effort in CRREL's refrigerated ice tank to give the reader a feeling for the scope and cost. Tasks 1–3 (apparatus design, procurements, construction, and installation) will require 5 months to execute. Tasks 4–5 (warm-water commissioning and model ice preparation) will require 1 month and will be executed in parallel. The ice-impact tests (Task 6) will require 0.5 months to execute; and the subsequent data analysis, report, and presentation (Tasks 7–8) will require 1.5 months. Thus, the estimated total project time is 8 months.

Table 3. Cost estimate for large-scale ice-impact tests.

Task No.	Description	Labor	Equipment	Facilities and Travel	Direct Costs	Overhead	Total
1	Apparatus detail design	$9,380			$9,380	$7,504	$16,884
2	Instrument procurements	$21,050	$79,500		$100,550	$80,440	$180,990
3	Apparatus construction and installation	$14,020	$3,000	$4,250	$21,270	$17,016	$38,286
4	Warm-water commissioning tests	$14,820		$4,250	$19,070	$15,256	$34,326
5	Model ice preparation and property measurements	$23,340	$3,000	$4,000	$30,340	$24,272	$54,612
6	Ice-impact tests	$26,200		$17,500	$43,700	$34,960	$78,660
7	Data analysis	$33,820			$33,820	$27,056	$60,876
8	Report, presentation, and conference	$22,420		$15,000	$37,420	$29,936	$67,356
Subtotals		$165,050	$85,500	$45,000	$295,550	$236,440	$531,990

6 Concluding Remarks

The rapid decline of the sea ice extent in the Arctic Ocean is leading to increased use of those waters. To protect U.S. sovereignty concerns and to support search and rescue obligations in the Arctic, the U.S. Navy expects to operate in waters with areal ice concentrations of up to 40% in the marginal ice zone as indicated in the U.S. Navy Arctic Roadmap. This requirement raises serious concerns about the ability of Navy vessels—which were not designed for operation in ice-infested waters—to meet these new operational requirements.

The IACS Polar UR is an industry-vetted set of design requirements for ships operating in ice-covered waters with the prime distinction being that the ice-load model that drives these requirements makes certain assumptions that may not be relevant to U.S. Navy surface vessels. For example, the Polar UR assumes that the bow has a small entry angle to promote the downward deflection of the ice to engage the flexural failure mode. In addition, the ice-impact model assumes that all of the effective kinetic energy transferred from the ship to the ice is converted to crushing energy, which may be appropriate for transit through level ice or impacts with very large floes but may not be adequate for ships impacting smaller and thinner floes where momentum transfer should play a more prominent role in determining the impact forces.

Even more to the point is that the sea ice mechanics are poorly understood. This is exemplified by the lack of consensus regarding pressure–area relationships that currently govern many ice-load models. Improvement of this understanding will require carefully controlled physical model testing with well-characterized ice properties and detailed information about the impact pressures and how the momentum is redistributed as a result of the impact.

The present effort evaluated current approaches to estimating the ice loads from impacts between ships and ice, summarized physical modeling consideration, such as model ice composition and properties, and surveyed the existing refrigerated ice tank facilities that exist worldwide. It also briefly outlined the background and status of analytical methods and experimental capabilities on hand to address the lack of impact data relevant to more vertically sided Navy hull forms and pointed out the deficiencies in these areas.

The last section of this report outlined a physical modeling approach and related analytical effort to improve the sea ice mechanics as related to ice–ship impacts. The proposed measurements would use an impactor instrumented with pressure panels, high-speed video, and an accelerometer-instrumented ice floe. This approach will provide much needed details of the contact patch shape, area, and pressure evolution throughout the impact process and the resultant momentum of the ship and ice floe. This information will in turn lead to a much-improved understanding of the partitioning of energy between ice failure and momentum exchange. The work would be conducted in the CRREL refrigerated towing tank facility, which is the only facility of its kind in the United States.

In conclusion, it is recommended that U.S. Navy couple their investments in the numerical modeling of ice impacts on ships with a focused physical modeling effort that will provide the ground-truth data necessary for accurately, economically, and quickly determining the safe operating speeds for its existing ships across the range of marginal Arctic ice conditions in which it may be necessary to operate.

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14. ABSTRACT
The U.S. Navy may need to operate its existing surface ships in Arctic marginal ice zones with ice concentrations up to 40%. To achieve this goal, the Navy must determine safe operational speeds as a function of ice concentration, floe size, and ice strength for its vessels. However, existing ice-impact models and safe-speed guidance for ships have derived from physical modeling and full-scale experience with ice-capable hull forms that have shallow entry angles to promote flexural ice failure preferentially over crushing failure. These models and associated guidance are unlikely to provide accurate estimates of ice forces on the more vertical-sided hulls that are characteristic of U.S. Navy vessels.

To address the lack of datasets relevant to the ice impacts on U.S. Navy vessels or like hull forms, this report proposes a series of 1:5 scale tests of ice impacts with a simplified "indentor" to obtain the data needed to inform and validate numerical models of ice impacts with Navy ships. These large-scale tests will provide important benchmark data to support the development of numerical testbeds where ice-impact forces under various operational scenarios are estimated, thus providing effective safe-speed and design guidance for existing Navy ships in Arctic marginal ice zones.

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